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Title: Ultra-Sensitive Sensors for Weak Electromagnetic Fields using High-Tc SQUIDs for Biomagnetism, NDE, and Corrosion Currents

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deflects <25 μm. Therefore, a thicker and stronger material such as quartz ultimately reduces the SQUID-sample distance. Kapton will remain useful in tests where minimal SQUID-to-sample separation is not critical as it is much less expensive and fragile. The preliminary results shown here are taken with a Kapton window.

The thermally conductive adhesive used to couple the SQUID to the sapphire cold-finger was also investigated. The material must have a high thermal conductivity as well as be easily removable at room temperature yet adhesive at cryogenic temperatures. Vacuum greases have traditionally been used for this purpose. Specific vacuum grease adhesive and thickness were optimized by affixing a precision thermistor to the tip of the cold finger with various materials and configurations. The same test apparatus was used to determine the optimal amount of super insulation to use and the temperature at various distances from the window.

The first data with the SQUID microscope was acquired three to six months ahead of schedule. It should be noted that neither the microscope nor the sample motion system were in optimal configuration. The motion control system for the first data was not implemented, therefore "scanning" was limited to one dimension by hand. Realistic position accuracy and reproducibility is a few millimeters. Also, a Kapton window was used limiting the SQUID to the sample separation to ~20 mm, consequently drastically limiting the spatial resolution to that scale. However, we were still able to take very promising data. **Figure 2** shows the results of a low-resolution scan of a 1.5-mm thick aluminum plate with a 6.35-mm slot cut out of it (diamonds), and a 1.5-mm thick aluminum plate with no slot (squares). We also acquired data for the slotted plate hidden under a similar plate with no slot (triangles). The difference between the slotted and solid plates is striking, and there is clear evidence that the slot can be seen even with a plate covering it [**1**].

System improvements were made by better centering of the induction coil and automated motion control for precise scan spacing (though sample-to-sample reproducibility was not implemented). The SQUID-sample distance was also reduced somewhat by better sample positioning, although this is difficult to quantify in our present set-up to better than ~10 mm. **Figure 3** presents data taken with a 1.5-mm thick aluminum plate with a 375-μm wide crack (diamonds), as well as data from a similar plate with no crack (squares), a plate with no crack covering the plate with the crack(triangles), and two plates with no cracks (circles). These first results are extremely encouraging as there was no difficulty in seeing the induced material defects. Preliminary examination of a stress fracture in a Ta-W hemicylinder indicates even smaller feature sizes can also be observed.

Development of HTS SQUIDs and SQUID Magnetometers

SQUIDs are state-of-the-art ultrasensitive devices that detect extremely weak magnetic fields. The discovery of high-T_c superconductors has led to intense interest in the development of SQUIDs and SQUID magnetometers based on these new materials. Josephson junctions, which are the key components in a SQUID, have been fabricated with different device constructions. The most widely investigated junction structures are bi-crystal grain-boundary, step-edge grain-boundary, and step-edge superconductor/normal-metal/superconductor (SNS). The ramp edge-geometry SNS junction, shown in **Figure 4**, is imposed of top and bottom superconductor electrodes separated by a normal layer. The active area of the device is located at the edge of the ramp where the N-layer is sandwiched between the top and bottom superconductor electrodes. Ramp edge-geometry SNS configuration provides several advantages over the other configurations. The most important feature from this SNS scheme is that the junction can be put anywhere on a chip without affecting other devices. This feature makes it possible to fabricate more complicated circuitry. Since the junction performance depends on the N-layer thickness and resistivity, one can control the electrical properties of the N-layer to fabricate Josephson junctions for specific applications. Most significant, external magnetic fields up to about 1G do not influence the noise of the SQUIDs fabricated using ramp edge SNS technology. It has been speculated that the junctions are intrinsically shielded from external magnetic fields by the Meissner effect in the top electrode.

Experimental results have shown the importance in the control of the interface between N and S to improve the junction performance based on the ramp SNS technology. Various groups have tried different N materials for the fabrication of edge-geometry SNS junctions. At Los Alamos, we have been using very unique approaches to solve the technical problems. By engineering the N-layer and/or superconductor electrode materials through process and device designs, we have successfully fabricated the best ramp-edge SNS dc SQUIDs and SQUID magnetometers reported.

We pursued two different approaches to improve the device performance. In the first, we use a gradient N-layer instead of an abrupt one to release the physical and chemical incompatibility between the N-layer and the YBCO electrode. By using such a gradient N-layer design, it is expected that the lattice strain can be spread out over several interfaces instead of being accumulated at one interface. It is also expected that a good chemical, thermal, and structural compatibility between adjacent layers can be accomplished through such a gradient variation of Pr-doping concentrations. This approach is totally different from the conventional one where a single N-layer material is used. In the second approach, we engineer the superconductor material using Ag-doped YBCO as electrodes, which substantially improves the controllability and reproducibility of the process.

To fabricate SQUIDs with a ramp edge-geometry SNS configuration as shown in **Figure 4**, (100) oriented $LaAlO_3$ wafers (3" in diameter), commercially available from AT&T, were diced into 1 x 1 cm^2 chips used as the substrates. A pulsed laser deposition (PLD) technique was used to deposit both top and bottom Ag:YBCO electrodes, N-layer PBCO, and insulating layer CeO_2. The depositions were done at a temperature of 775 °C and an oxygen pressure of 200 mTorr for Ag:YBCO but at 650 °C for CeO_2. Conventional photolithography was used to define the location of the device and ion milling with 250 eV Ar ions was used to etch the film and to form the ramp edge. The details of the fabrication procedures can be found elsewhere [**7**]. The angle between the edge and the substrate surface, as confirmed by atomic force microscopy, was controlled in the range of 15° [**8**]. The N-layer PBCO and the top Ag:YBCO electrode were deposited after stripping off the photoresist and cleaning the edge surface. The substrate temperature and oxygen pressure during both N-layer and top Ag:YBCO electrode deposition were the same used for the deposition of bottom Ag:YBCO electrode. The most important thing we would like to point out is that the use of Ag-doping in YBCO not only enhances the performance of the devices but also improves the yield of devices [**3**].

The SQUIDs fabricated in such a way showed well-defined RSJ-like I-V curves at liquid nitrogen temperature. The critical current (I_c) and interface resistance (R_n) scaled fairly well with the device geometry on the same chip. The measured R_n value from the junction was also quite close to that evaluated from the physical geometry of the PBCO barrier layer. This implies that the interface resistance is not a controlling factor in determining the device performance. Many SQUIDs fabricated on the same chip or different chips from different fabrication batches showed voltage modulation above 25 μV at 75K, where the SQUIDs have a square center hole with dimensions of either 5x5 μm or 10x10 μm. Our best results showed a voltage modulation of 49 μV at 75K [**3**].

The relatively higher SQUID voltage modulation and flux-to-voltage transfer function (the highest $\delta V/\delta\Phi$ is around 170 $\mu V/\Phi_0$) makes the SQUID fairly quiet ($\Phi_0 = 2.07 \times 10^{-15}$ Wb is a flux quantum). The flux noise of the devices at 75K showed a 1/f dependence at low frequency having values of root mean square below 100 $\mu\Phi_0$ (the best value in the range of 30-40 $\mu\Phi_0$) at 1Hz and around 5 $\mu\Phi_0$ above 1 kHz in the white noise region. The measurement was done with dc bias currents without any noise reduction scheme.

The technology was successfully applied to fabricate directly coupled SQUID magnetometers. The pickup loop has an area of 6-mm x 3.5-mm in our design. There were two magnetometers on 1-cm x 1-cm $LaAlO_3$ substrate. The devices routinely display IR products above 120 μV and a V/Φ above 100 $\mu V/\Phi_0$. The processing was quite controllable. For example, the values of voltage modulation for the two magnetometers on the same chip were 21 μV and 23 μV at 75K, respectively. The peak-to-peak value was around 37 μV at 75K. This value is the best reported so far for a SQUID magnetometer based on edge-geometry SNS construction. The curves are perfectly periodic and show no hysteresis while sweeping the field back and forth. The magnetometer magnetic field noise based on the above design was around 2pT at 1 kHz. Improvement of the device field sensitivity by increasing the area of the pickup loop and optimizing the device design is underway.

To increase the field sensitivity of the SQUID magnetometers, we designed our second magnetometers with a bridge width of 5 μm for each junction. The slot was 54-μm long and 5-μm wide. The pickup loop had an outside dimension of 8.5-mm x 7.5-mm and line width of 1 mm patterned from the top electrode. The SQUID inductance was near 35 pH. We were able to tune I_c and R_n by varying the N-layer thickness. We had fabricated directly coupled SQUID magnetometers with I_c as low as 17 μA and R_n as high as 4.4 Ω at 75.5K for each junction. A maximum voltage modulation of 20 μV at 75K was achieved at a bias current slightly higher than the critical current of the junction. The combination of increasing the SQUID inductance and the pickup loop area by factors of 1.75 and 2.8, respectively, reduced the field noise of the directly coupled SQUID magnetometer by a factor of 5 compared to our first design. The rather small effective area, estimated to be 0.04 mm^2, limited the field noise to modest values of 400 fT. Nevertheless, the SQUID magnetometers were cycled from zero field to 500 mG and returned to zero field for the noise measurement; no change in the SQUID signal amplitude was evident.

SQUID Hardware Gradiometery for Noise Rejection

Conventional wire-wound gradiometers cannot be readily made with existing high temperature superconductor (HTS) technology due to the lack of practical HTS wire.

Nevertheless the ability to perform gradiometry is a valuable tool for reducing the noise from background magnetic fields and enabling these devices to perform in magnetically unshielded or lightly shielded environments such as would be practical for NDE applications. One method that has previously been explored involves "electronic" gradiometry, where the signal from two (sensor and background) HTS SQUIDs are digitally subtracted in a computer. However, the dynamic range of both SQUIDs in this method may largely be consumed with ambient noise, and the signal of interest is only present after signal processing.

To address these issues, two different systems for noise cancellation (first order gradiometers) have been developed using two similar HTS SQUIDs. "Analog" gradiometry is accomplished in hardware by either 1) subtracting the signals from the sensor and background SQUIDs at a summing amplifier (parallel technique) or 2) converting the inverted background SQUID signal to a magnetic field at the sensor SQUID (series technique). Balance levels (ability to reject a uniform background magnetic field) achieved are $2x10^3$ and $1x10^3$ at 20 Hz for the parallel and series methods, respectively.

We also investigated the balance level as a function of frequency. The time delays (phase differences) affect the balance levels of the two sets of SQUID electronics. We found that these delays, along with geometrical considerations, are the limiting factor for balance level for any electronic gradiometry system using two (or more) SQUIDs, a very different situation from the case with wire-wound gradiometers. We measured balance levels using a dipole field to study the performance of both the parallel and series devices functioning as gradiometers in an unshielded laboratory and compared with theory.

Both gradiometers were constructed using two HTS Mini-Mag SQUID magnetometers. Each SQUID was controlled via personal computer by a programmable feedback loop (PFL-100) and personal computer interface unit (PCI-100). The two SQUIDs were mounted in an axial gradiometer configuration, with their central axes aligned along a common Z axis with a 1-cm baseline.

For the "parallel" noise cancellation, the output of both the background and sensor SQUIDs went to a summing amplifier where the gains were adjusted and the difference was taken. The common mode rejection coefficient of the amplifier is 93 dB at 1 kHz and 108 dB at 100 Hz. For the "series" noise cancellation the output of the low sensitivity background SQUID was sent to the amplifier for gain adjustment and inversion and subsequently into a test input on the PC-100 unit that corresponds to the high sensitivity sensor SQUID. The signal was then summed with the modulation/feedback current, effectively nulling the background field present at the sensor SQUID. The series technique